Lagrangian Floats for CBLAST

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LONG-TERM GOALS

I seek to understand the dynamics of the ocean boundary layer beneath hurricanes and the resulting air-sea fluxes which drive it with the goal of improving ocean models at high wind speed.

OBJECTIVES

To measure turbulence properties and fluxes in the ocean boundary layer beneath hurricanes and relate them to hurricane properties and fluxes measured by others. To model the measured boundary layer properties using Large Eddy Simulation (LES) techniques with the twin goals of testing the models and investigating the boundary layer physics using the models.

APPROACH

Measurements. Neutrally buoyant Lagrangian floats were air-deployed into hurricanes during the 2002, 2003 and 2004 hurricane seasons. The floats are designed to be used in energetic turbulent flows such as those found in the top and bottom boundary layers of the ocean. A combination of accurate ballasting, compressibility matched to that of seawater and high drag is used to make these floats follow the motion of water parcels accurately (D'Asaro 2003). Water velocity is inferred from the motion of the floats; high frequency fluctuations in velocity can be used to infer dissipation rate (Lien and D'Asaro, 2005) and covariance of vertical velocity with scalars can be used to compute heat and other fluxes (D'Asaro, 2004).

Modeling. The LES modeling work is being conducted by Ramsey Harcourt and Eric D'Asaro. Our starting point is a standard LES scheme using a subgrid closure with active kinetic energy as implemented in Harcourt et. al (2002) for the simulation of deep convection in the Labrador Sea. The standard implementation of vortex force interaction between surface wave Stokes drift (Skyllingstad and Denbo, 1995; McWilliams *et al*, 1997) is modified to simulate the mean Lagrangian velocities measured by floats in the ocean. Careful attention has been paid to the role of surface waves in forcing boundary layer turbulence. This model includes the ability to simulate the trajectories of both perfectly Lagrangian and realistically imperfect floats. This allows a direct comparison between the Lagrangian float observations and the Lagrangian model output. Similar work funded by NSF using float data at lower wind speeds will allow these results to be extended across a broad range of conditions.

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WORK COMPLETED

Hurricane Frances – Four floats were deployed into Hurricane Frances on August 31, 2004 as part of an overall 28 element CBLAST array. Two survived, indicating that our air deployment system still needs work. The results from the remaining two are spectacular, with the floats measuring the properties of the ocean boundary layer under nearly 60 m/s winds. Targeting of the storm, done by the PI using information from the National Hurricane Center, was nearly perfect. The data was supplemented by profiling 'EM-APEX' floats from Tom Sanford as part of an ONR funded SBIR. The combination of the boundary layer Lagrangian floats, which measure fluxes, and the profiling floats, which provide the spatial context for these measurements, including velocity, gives a unified view of the entire boundary layer. The floats were recovered on a cruise in late October, 2004.

Modeling The numerical effort has concentrated on modeling the upper ocean data gathered in Hurricane Dennis. Preliminary runs clearly indicated the importance of driving the ocean with accurate surface wave fields, since the modeled upper ocean turbulence is strongly related to the wavefield through both the vortex force of Craik and Liebovich (1976) and through parameterized wave breaking. Given the sensitivity of model-data comparisons to this forcing, accurately characterizing the surface wave field coincident with float measurements has been crucial. Directional wave spectra have been extracted from scalar wave spectra measured at a nearby NDBC buoy. A number of ad hoc assumptions are necessary to do this. Separately, and in addition, we have also been using spectra generated by the WaveWatch III model in cooperation with I. J. Moon (URI). This model has been shown to yield good directional wave spectra in hurricanes (Moon et. al, 2003). This coupling is part of an overall effort to make energy transfers into upper ocean models from surface waves consistent with energy losses in surface wave models. Modeling for comparison with hurricane Frances observations will follow.

RESULTS

Boundary layer structure. Fig. 1 shows the evolution of the upper ocean density structure determined from the combination of data from the two types of floats. The results show a 5 layer structure to the boundary layer. The *near-surface layer,* extending to about 10m is directly influenced by surface waves and their bubbles (see below). The *mixed layer*, extending to about 40m, is delineated by the excursions of the Lagrangian floats. It is fully turbulent as measured by the Lagrangian floats. The underlying *weakly stratified layer* is only intermittently turbulent, but with a Richardson number (measured by the EM-APEX floats) maintained near ¼. This layer occupies roughly half of the entire boundary layer depth. Its importance has been suggested previously but this is the clearest example yet measured. The *mixed layer base*, shows a clear increase in stratification and is marked in Fig. 1 by the dashed lines. This is bottom of the boundary layer. The *laminar interior*, below this, shows little sign of storm induced mixing.

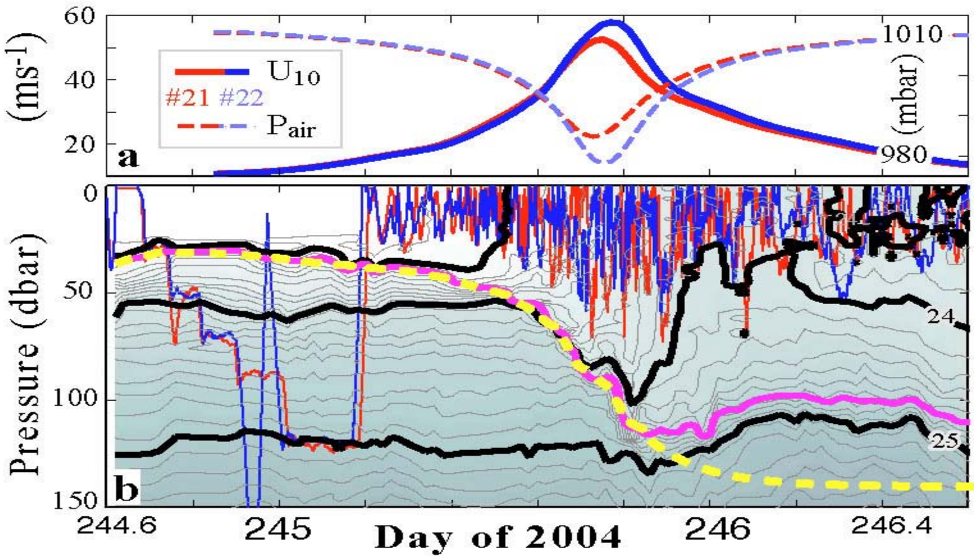

Fig 1. Evolution of the ocean boundary layer under Hurricane Frances. a) Wind speed (solid line) and atmospheric pressure at the location of the two floats (red and blue) as determined from the NOAA H*WIND product. Wind speed rises to 57 m/s. b) Ocean density (contours and shading) shows a 20 m mixed layer before the storm, rapidly deepening to 120 m as the storm passes. The Lagrangian floats, however, oscillate within the upper 40 m, indicating the extent of the fully turbulent boundary layer.

Heat Budget**.** The heat budget is one-dimensional through the time of maximum winds, but then rapidly become three-dimensional due to horizontal advection of heat. Fortunately, the three-dimensional effects become important sufficiently late that one-dimensional models are still useful. Accurate heat and salt budgets can be using a slightly modified mixed layer base depth shown by the yellow dashed line in Fig. 1. These are supplemented by the direct covariance flux measurements.

The cooling of the surface is entirely dominated by mixing of cold water from below. This is equivalent to about 20,000 Wm^{-2}. Air-sea heat fluxes, directly measured by the floats, are only a few percent of this, but appear consistent with existing bulk formulae. The strong upward mixing of cold water almost certainly results from strong shears generated by the wind stress, with the flux through the weakly stratified layer probably controlling this flux through shear instability.

Bubbles and Plumes**.** At the time of the largest winds, the near surface layer is filled with bubbles (see Fig. 2) at concentrations up to 0.1% by volume. This stratifies the near-surface layer with a density change of about 1 kg m^{-3} over a layer thickness of about 10m. A dynamical measure of this stratification is the Froude number $u_* \big/ \sqrt{g\rho' H}$, which has a value of about 1, indicating that the stratification is strong enough to inhibit the vertical transport. Transport between this layer and the interior occurs through strong downward plumes, as shown in Fig. 2. These may break through the bubble-induced stratification, by an instability mechanism in which the downward displacement of the bubbles causes them to shrink, thereby decreasing their buoyancy and enhancing the local vertical motion. In any case, the plumes clearly transport bubbles into the boundary layer interior, where they dissolve due to the increasing friction.

This has profound influences on air-sea gas flux in hurricanes, as described in a recent paper submitted to ***Nature***.

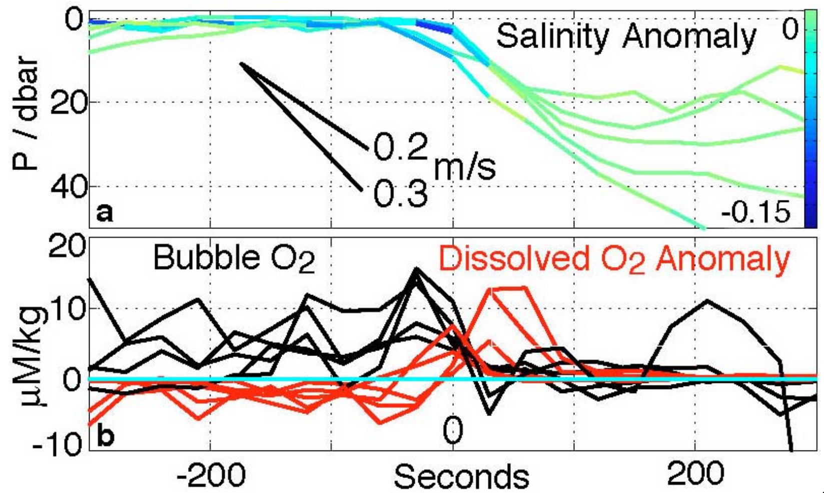

Fig. 2. a) Selected time-depth trajectories of Lagrangian floats, starting in the near-surface layer and plunging downward into the interior during the period of highest wind. The downward velocities are 0.2 to 0.3 m/s. Each trajectory is colored to indicate the measured salinity anomaly from the layer interior value. Salinities are fresher near the surface. I interpret this as due to bubbles in the water which decrease its conductivity. The anomalies correspond to bubble void fractions of up to 10^{-3} parts of air per part of water. b) Time series of Oxygen contained in the bubbles (black) and measured dissolved oxygen anomaly relative to the layer interior (red). As the near-surface water, tracked by the floats, descends into the boundary layer interior, the bubbles dissolve as indicated by the disappearance of the salinity anomaly at the same depth as the appearanceof the dissolved oxygen anomaly.

Modeling. Our modelling efforts for Hurricane Dennis (1999, 30 m/s wind speed) are nearly complete and those for Hurricane Frances (2004, 60 m/s wind speed) are now beginning. Results from Dennis include:

- The modelled vertical kinetic energy agrees well with the observations on the left side of the storm, but less well on the right side. This difference is not due to the buoyancy of the floats, but may be due to errors in the forcing.
- The modelled vertical kinetic energy can be modelled as $0.75\ u^{*2}\ (1 + 0.08/\ La_d^2)$, where u* is the friction velocity, U_s is the wave Stokes drift and La= $(u^*/\ U_s)^{1/2}$ is the Langmuir number. Thus, as in the case of more moderate winds, the vertical kinetic energy scales well on the wind stress with only a minor additional contribution from the Stokes drift.
- At moderate winds, the excellent scaling with u* and the good agreement between data and the levels of vertical kinetic energy predicted by models indicates that wave breaking does not contribute substantially to the overall level of kinetic energy in the boundary layer. However,

the agreement with data in Dennis is less good, leaving room for these processes to be potentially important at high wind speed.

- Comparison of the LES results with the predictions of the KPP model (Large et. al, 1994) suggests that the parameterized rate of entrainment may have to be increased 20-30% when the effects of Stokes drift is added. However, this correction may be small compared with other model adjustments necessary at high winds.

IMPACT/APPLICATIONS

The Hurricane Frances deployments demonstrate the capability to make detailed ocean measurements in hurricanes and other remote and difficult environments using air-deployed instrumentation from standard transport aircraft.

RELATED PROJECTS

None

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